New renormalization scheme in extended Higgs sectors for Higgs precise measurements

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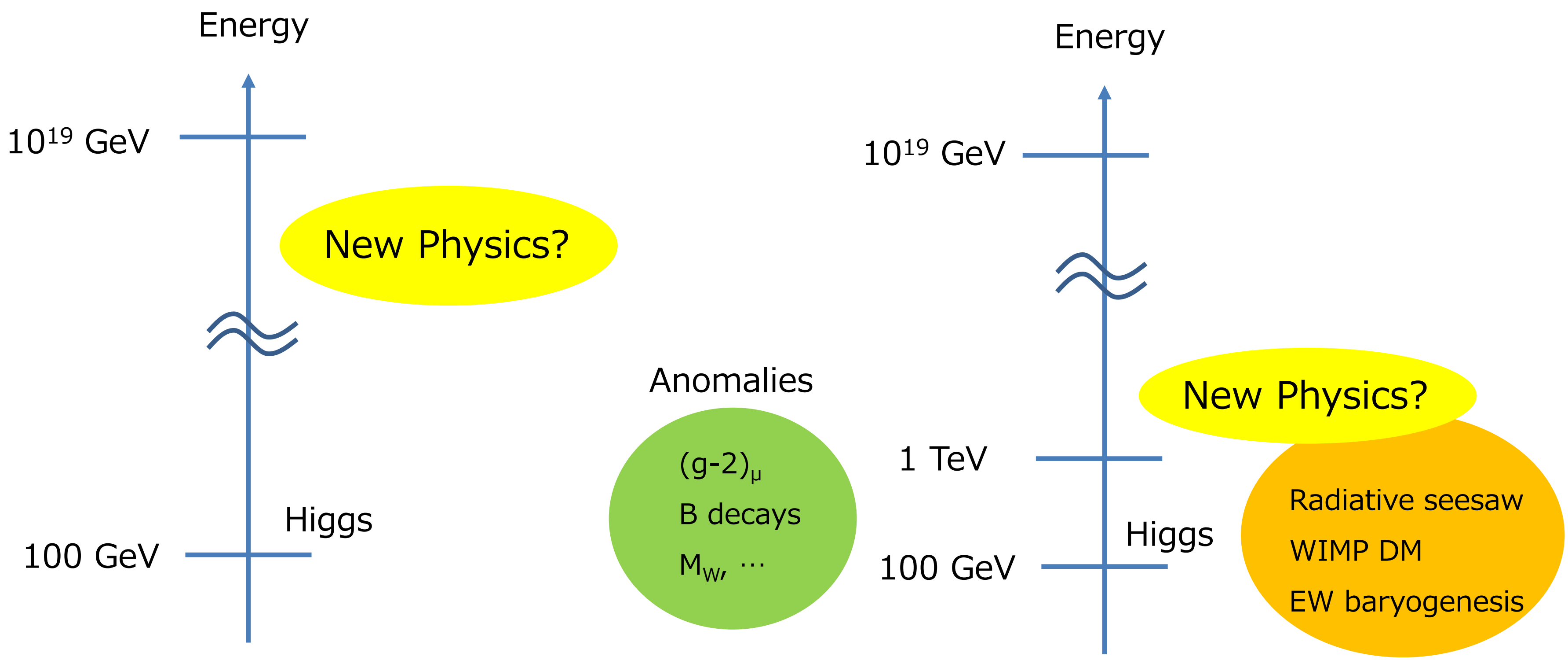
Higgs Physics: Current Status

Decoupling scenario

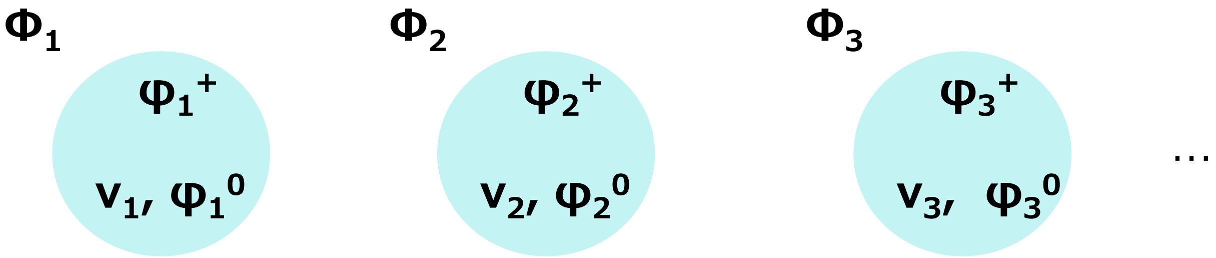
"Alignment" scenario



Non-minimal Higgs sectors often appear.

"Alignment" has been the keyword for non-minimal Higgs sectors!

What is the Alignment?



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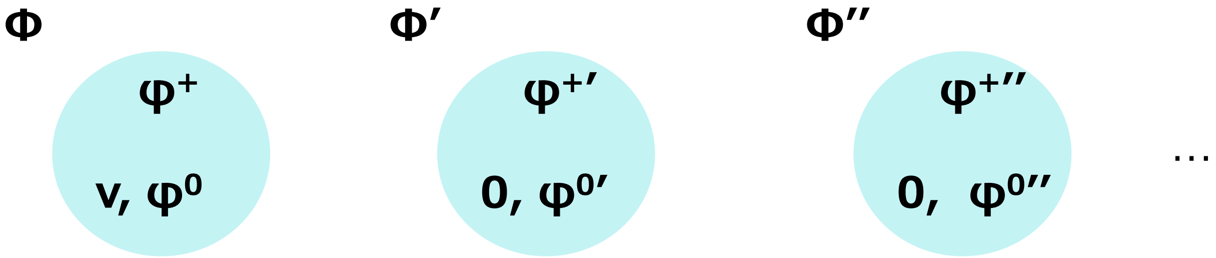

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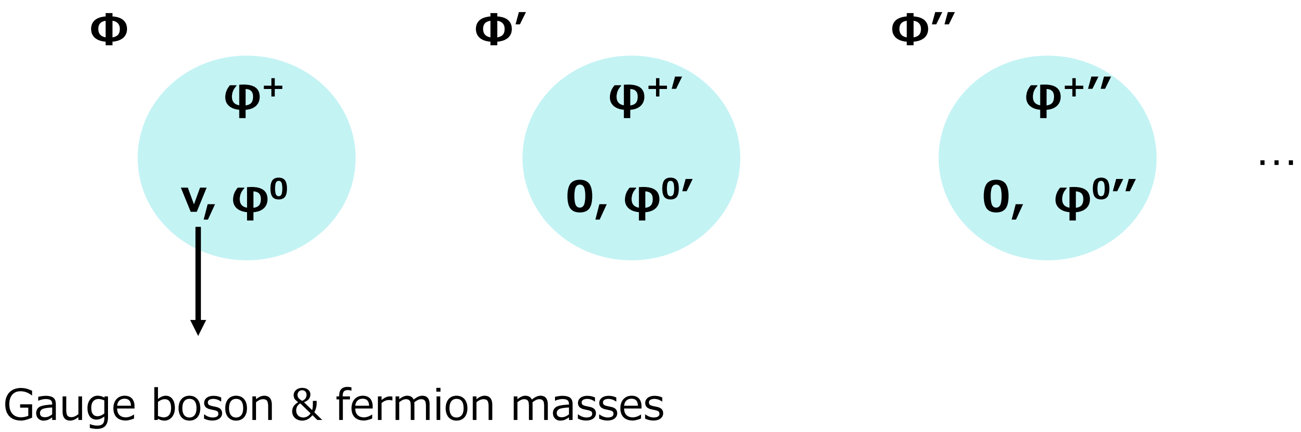

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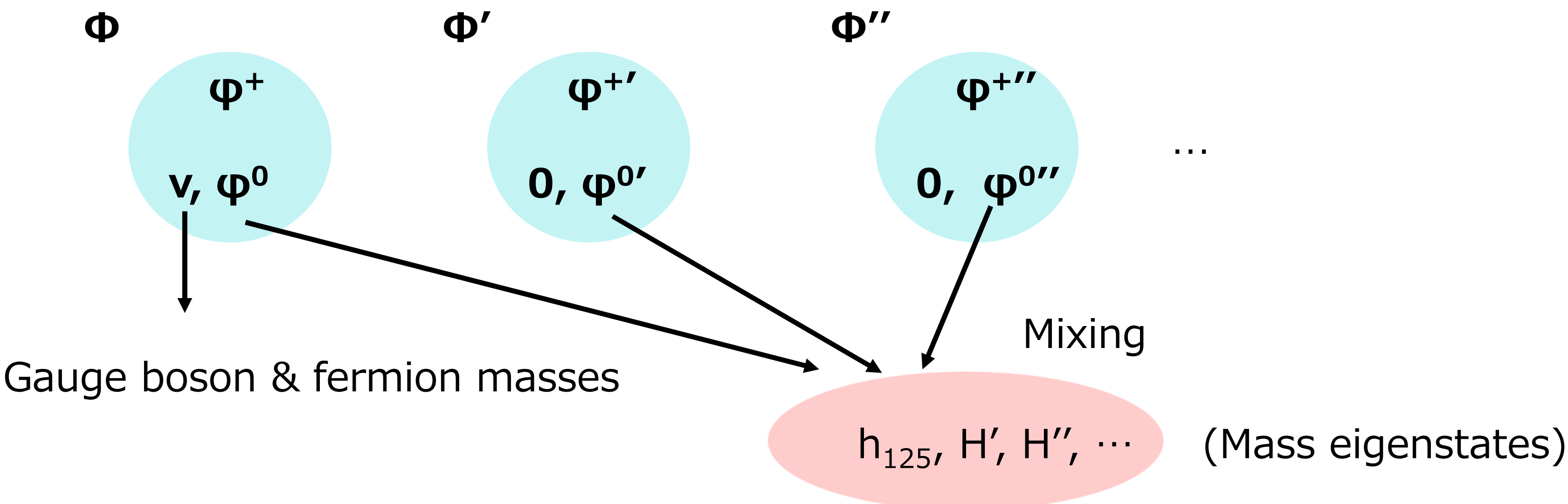
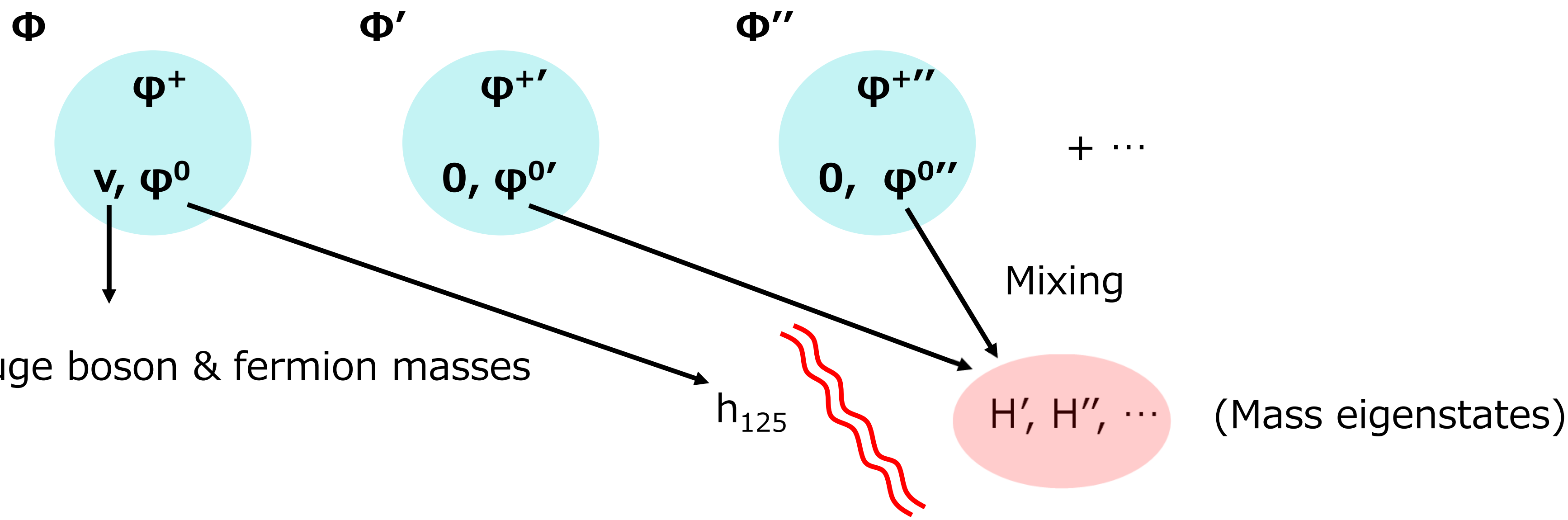


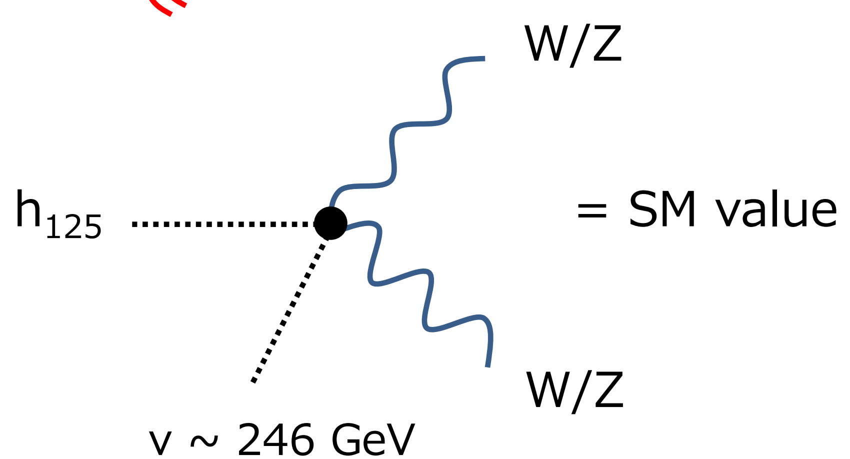
Generally, Re $[\varphi^0] \neq h_{125}$

What is the Alignment?

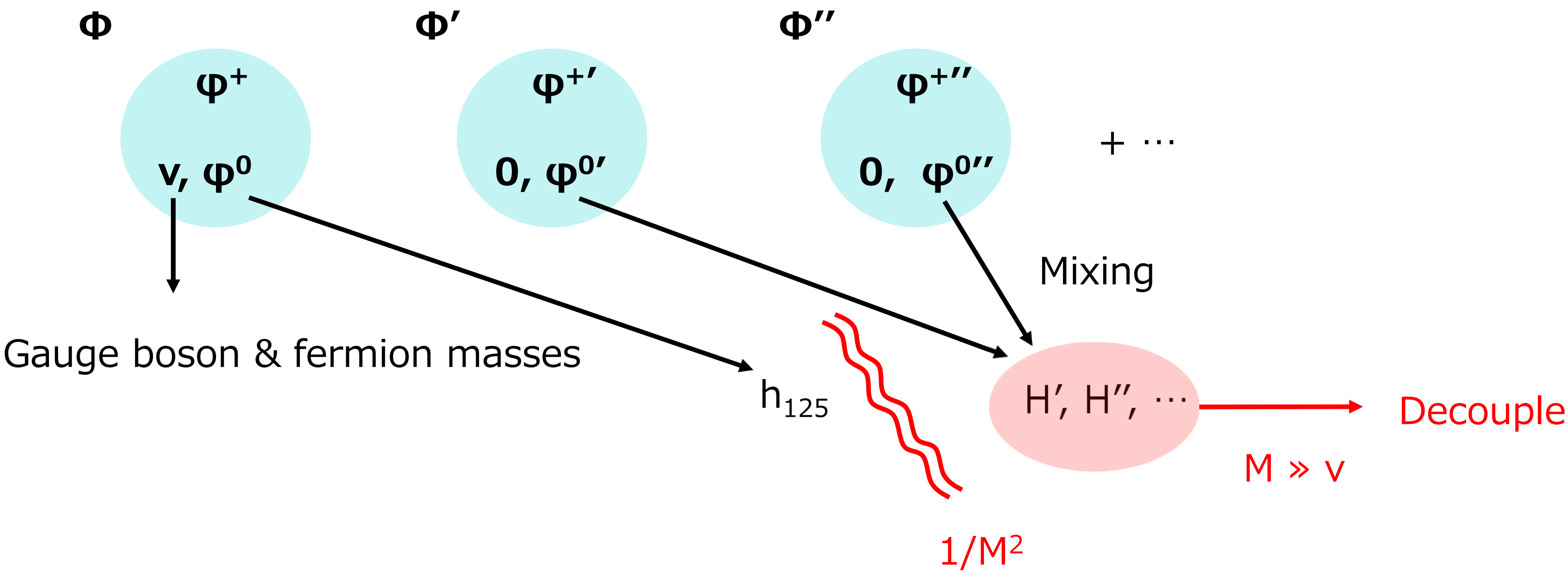


Generally, Re $[\varphi^0] \neq h_{125}$

Higgs alignment: Re $[\varphi^0] = h_{125}$



How to realize the Alignment?

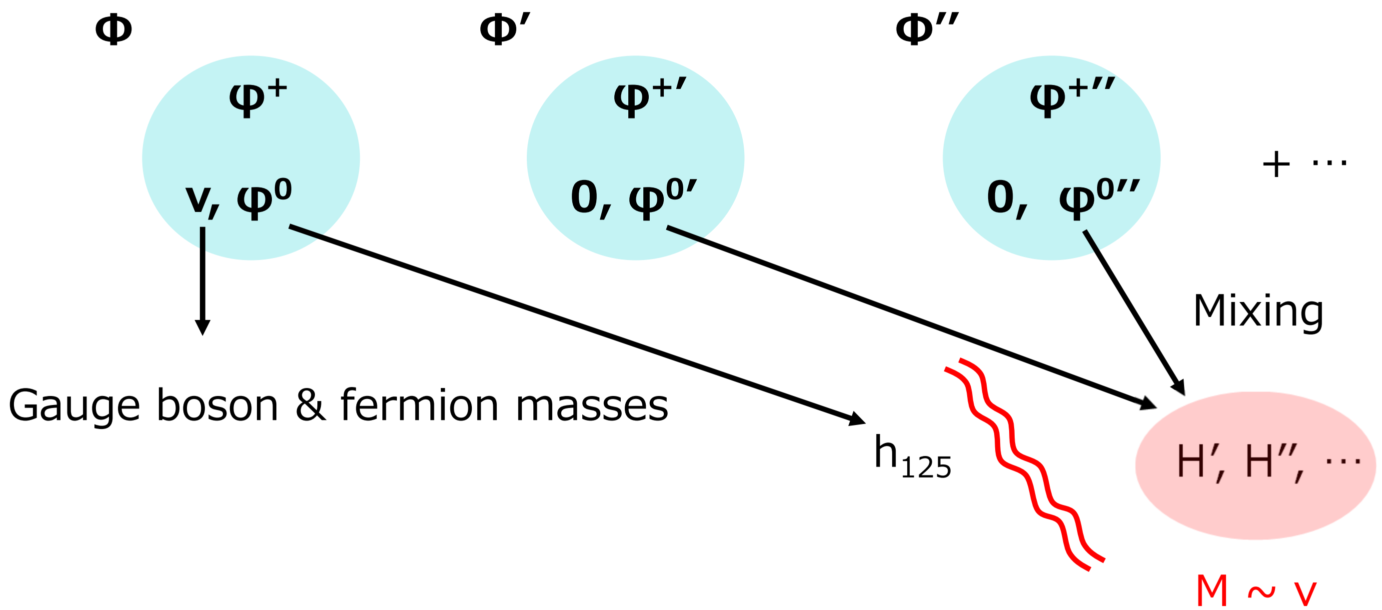


- If extra Higgs masses are much larger than v, the mixing is suppressed by $1/M^2$, and the Higgs alignment is deduced.

Appelquist and Carazzone (1974)

- This is also true at quantum levels due to the decoupling theorem.

How to realize the Alignment?

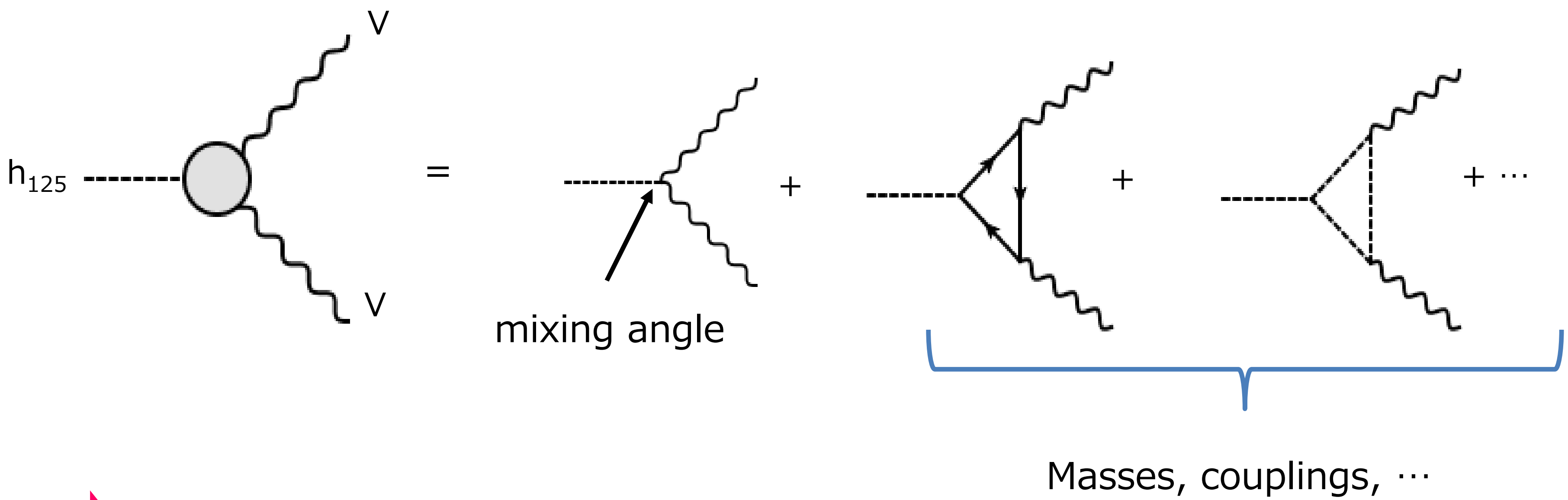


- The mixing can be O(1), but we can take the mixing angle ~ 0 by some mechanism or by hand **(alignment w/o decoupling)**.

Mixing angle describes "alignmentness".

What happens at quantum levels?

Higgs alignment at quantum levels



Mixing angle no longer describes the alignmentness.

We can define the alignmentness by the deviation of the coupling or decay rate,

but it cannot simply be expressed by model parameters ⋯.

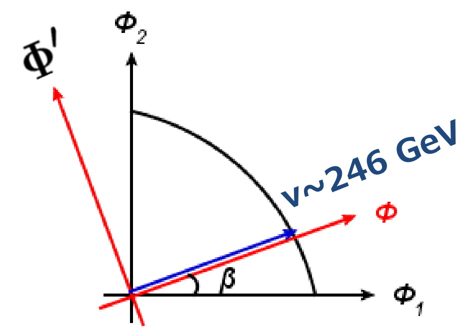
We propose a new reno. scheme such that the mixing describes the alignmentness.

2 Higgs Doublet Models (CP-Conserved)

- **Higgs basis** *Davidson, Haber PRD71 (2005)*

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Phi' \end{pmatrix}$$

$\tan\beta = v_2/v_1$



NG boson

Charged Higgs

$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h_1' + v + iG^0) \end{bmatrix}$$

$$\Phi' = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + iA) \end{bmatrix}$$

CP-even Higgs

CP-odd Higgs

- **Higgs mixing**

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} = \begin{bmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{bmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

125 GeV Higgs

- **Decoupling limit:** $M^2 \to \infty$

$m_h^2 \sim \lambda v^2, \quad m_\Phi^2 \sim M^2 + \lambda' v^2$

$\Phi = H, A, H^\pm$

- **Alignment limit:** $\sin(\beta-\alpha) \to 1$

Higgs potential & Counterterms

- Higgs potential with a softly-broken Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$).

$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2[\Phi_1^\dagger\Phi_2 + \text{h.c.}]$$
$$+\frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$

- 8 parameters

m_h^2, m_H^2, m_A^2, m_{H+}^2, $\sin(\beta-\alpha)$, $\tan\beta$, v and M^2 $\quad M^2 = m_3^2/(\sin\beta\cos\beta)$

- Parameter shift

$x_i \to x_i + \delta x_i$

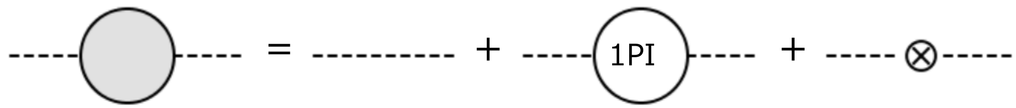
- Field shift

$$\begin{pmatrix} H \\ h \end{pmatrix} \to \begin{pmatrix} 1+\frac{1}{2}\delta Z_H & \delta Z_{Hh} \\ \delta Z_{hH} & 1+\frac{1}{2}\delta Z_h \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix} \qquad \begin{pmatrix} G^0 \\ A \end{pmatrix} \to \begin{pmatrix} 1+\frac{1}{2}\delta Z_G & \delta Z_{GA} \\ \delta Z_{AG} & 1+\frac{1}{2}\delta Z_A \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

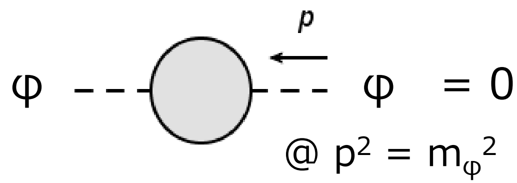
$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} \to \begin{pmatrix} 1+\frac{1}{2}\delta Z_{G^\pm} & \delta Z_{G^\pm H^\mp} \\ \delta Z_{H^\pm G^\mp} & 1+\frac{1}{2}\delta Z_A \end{pmatrix} \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

We have 20 counterterms.

Renormalization in the Higgs sector



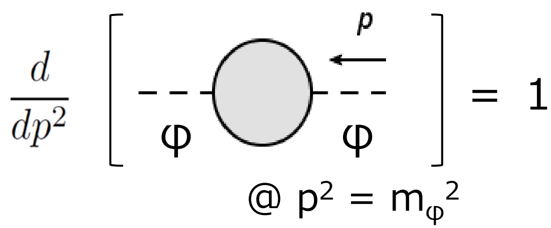
OS condition I:



δm_φ^2 (4)

(φ = h, H, A, $H^\pm$)

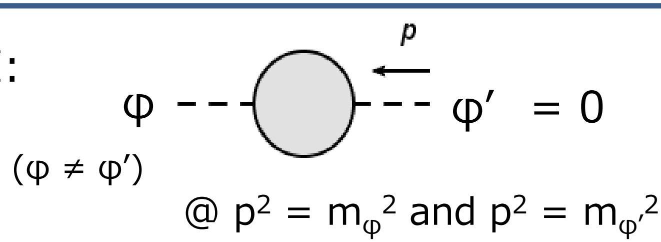
OS condition II:



δZ_φ (6)

(φ = h, H, A, $H^\pm$, G^0, $G^\pm$)

OS condition III:



δZ_{Hh}, δZ_{hH}, δZ_{GA},

δZ_{AG}, δZ_{H+G-}, δZ_{G+H-} (6)

Hollik (1990),…

δv : Ren. in the EW sector

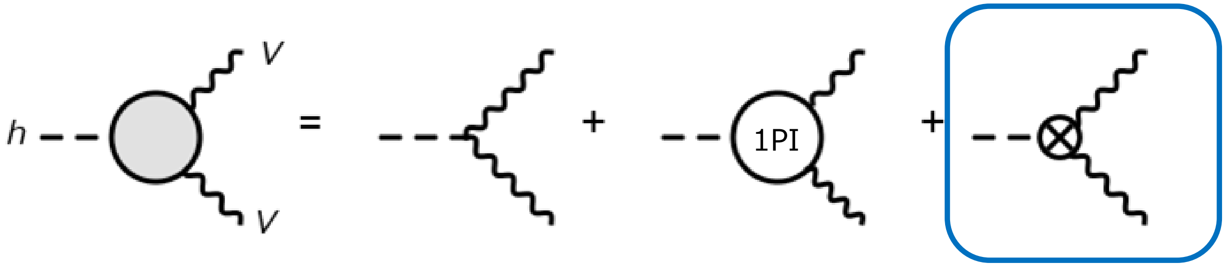
δM^2 : MS-bar

Kanemura, Okada, Senaha, Yuan (2004)

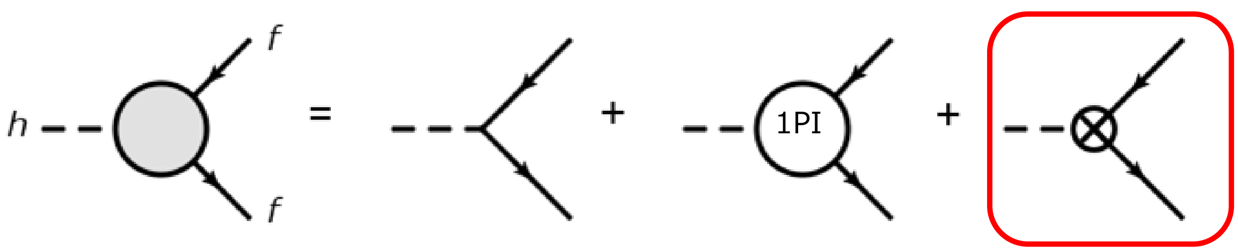
We need 2 more conditions to determine $\delta\alpha$ and $\delta\beta$.

New renormalization scheme

We exhausted all the 2-point functions. Let us consider 3-point functions.



$$\sin(\beta-\alpha) \to \sin(\beta-\alpha) + \underline{\cos(\beta-\alpha)\delta(\beta-\alpha)}$$

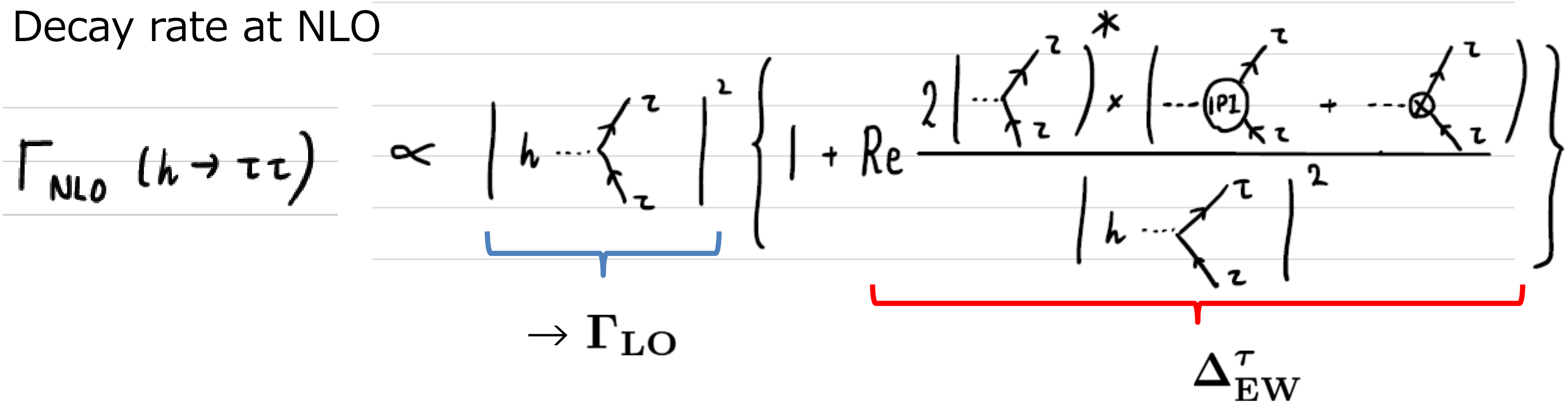


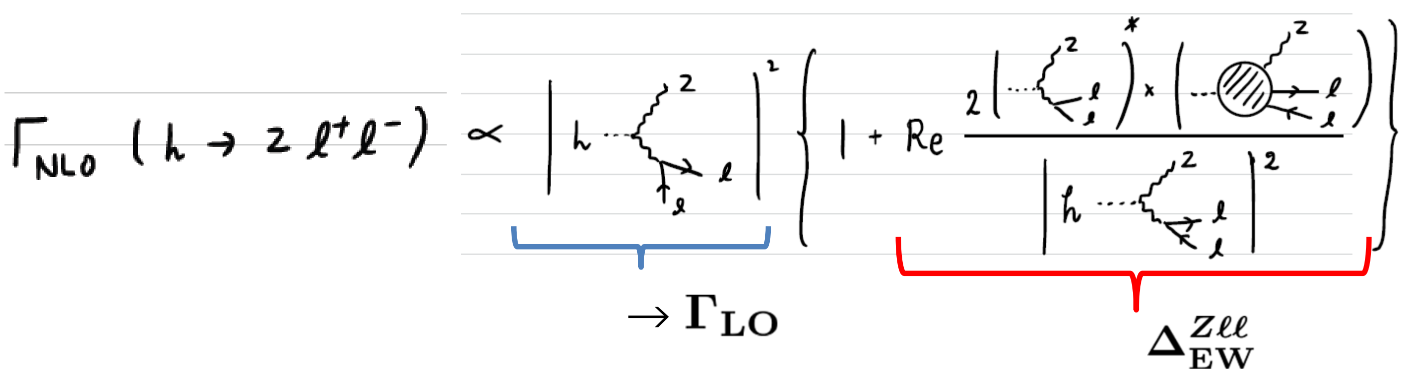
Type-I case:

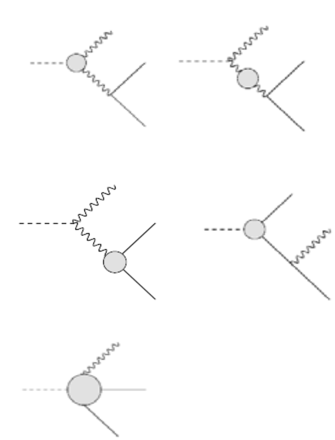
$$\sin(\beta-\alpha)+\cot\beta\cos(\beta-\alpha) \to \sin(\beta-\alpha)+\cot\beta\cos(\beta-\alpha)$$
$$+\underline{\left[\cos(\beta-\alpha)-\cot\beta\sin(\beta-\alpha)\right]\delta(\beta-\alpha)-\frac{\cos(\beta-\alpha)}{\sin^2\beta}\delta\beta}$$

New renormalization scheme

Decay rate at NLO

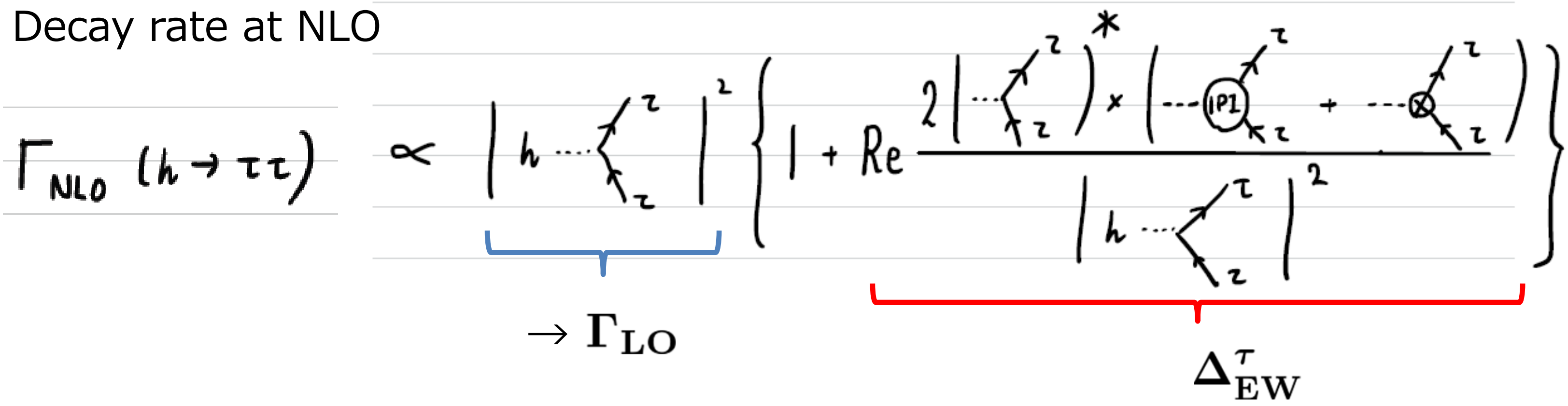


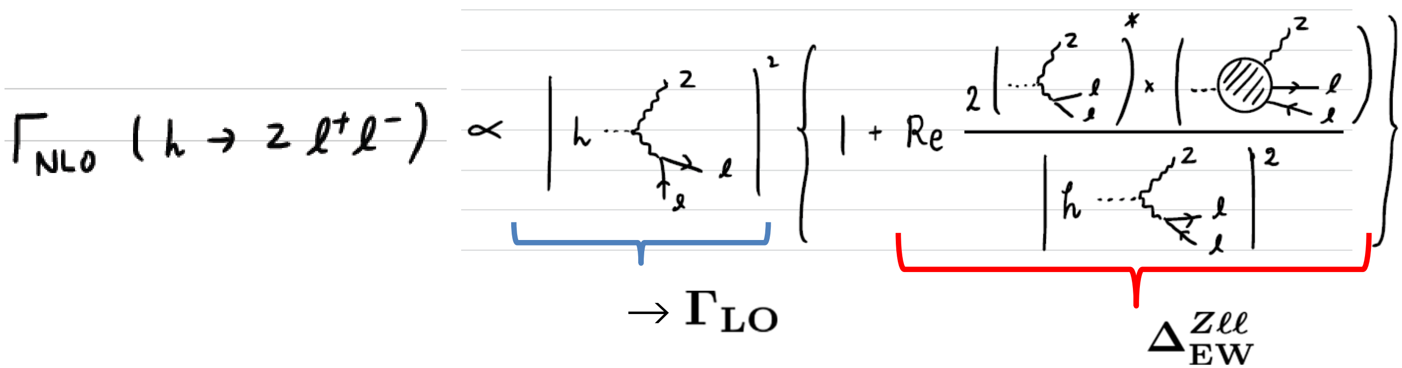


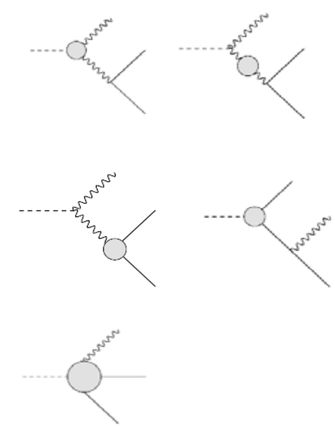


New renormalization scheme

Decay rate at NLO





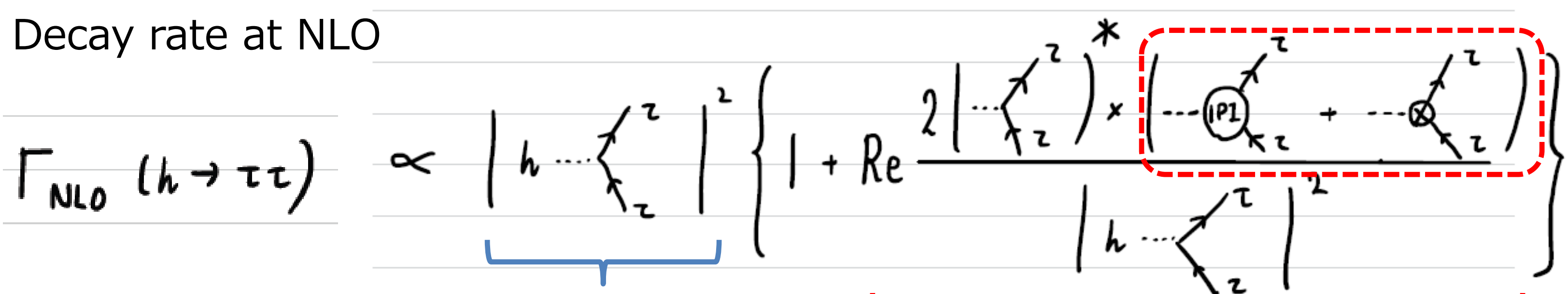


Renormalization conditions

$$\Delta^{\tau}_{\mathrm{EW}} = \Delta^{\tau}_{\mathrm{EW}}|_{\mathrm{SM}} \qquad \Delta^{Z\ell\ell}_{\mathrm{EW}} = \Delta^{Z\ell\ell}_{\mathrm{EW}}|_{\mathrm{SM}}$$

New renormalization scheme

Decay rate at NLO

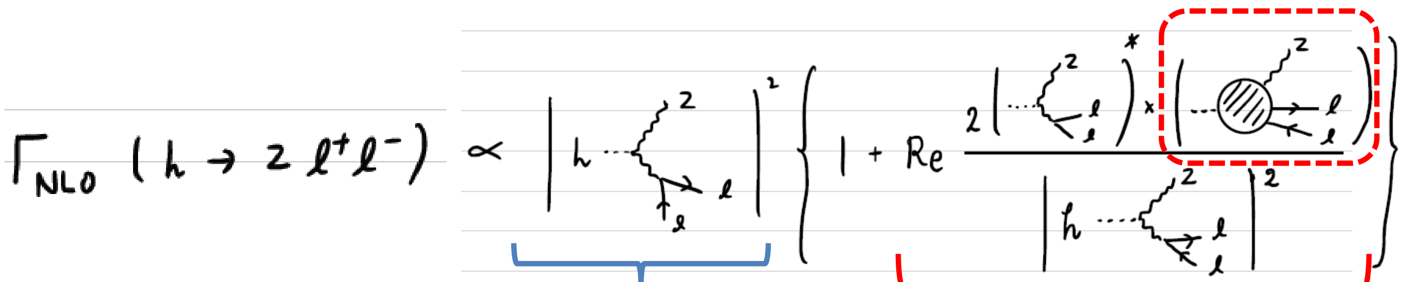


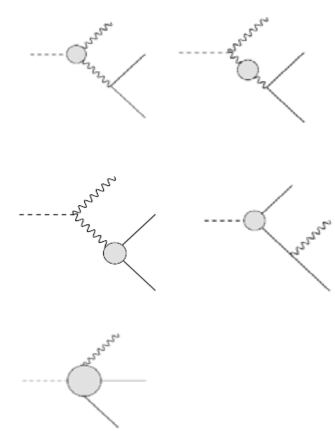
$\kappa_h^\tau \times \mathrm{SM}$

$\rightarrow \Gamma_{\mathrm{LO}}$

$\Delta^\tau_{\mathrm{EW}}$

$\sin(\beta-\alpha) \times \mathrm{SM}$





$\rightarrow \Gamma_{\mathrm{LO}}$

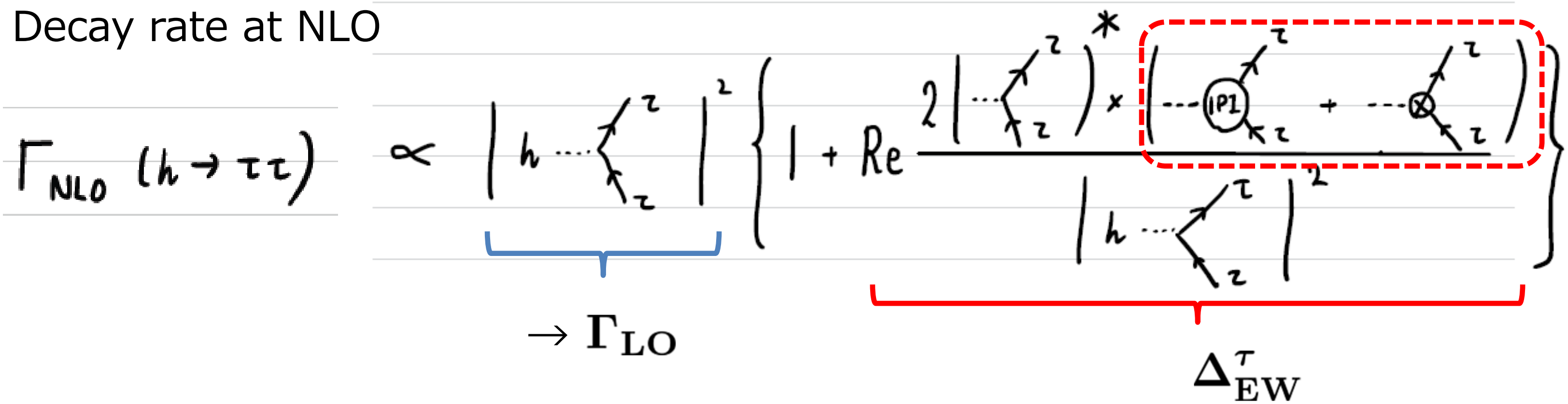
$\Delta^{Z\ell\ell}_{\mathrm{EW}}$

Renormalization conditions

$$\Delta^\tau_{\mathrm{EW}} = \Delta^\tau_{\mathrm{EW}}|_{\mathrm{SM}} \qquad \Delta^{Z\ell\ell}_{\mathrm{EW}} = \Delta^{Z\ell\ell}_{\mathrm{EW}}|_{\mathrm{SM}}$$

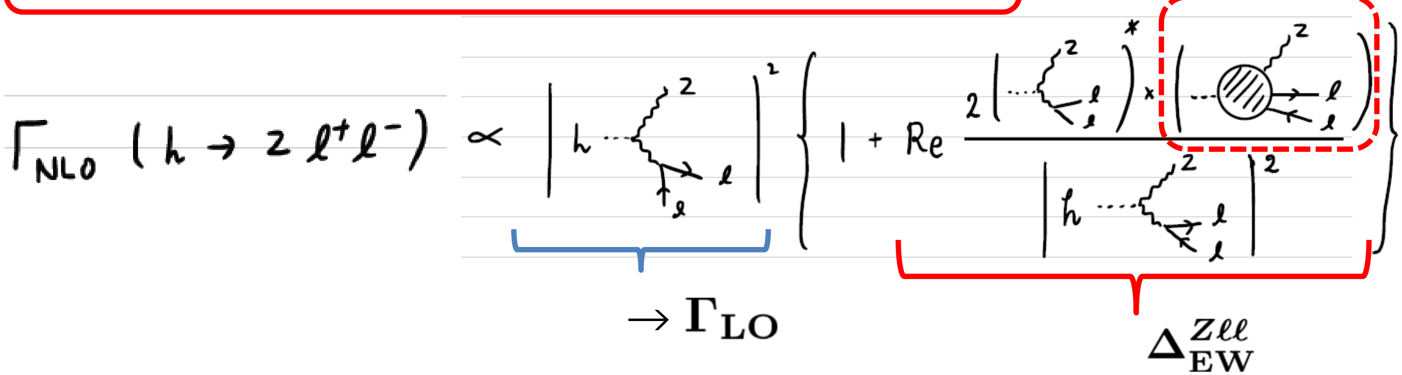
New renormalization scheme

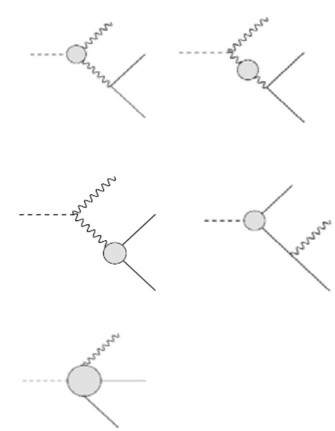
Decay rate at NLO



$$\Gamma_{\mathrm{NLO}}(h \to \tau\tau) = (\kappa_h^\tau)^2 \times \Gamma_{\mathrm{NLO}}(h \to \tau\tau)_{\mathrm{SM}}$$

$\sin(\beta - \alpha) \times \mathrm{SM}$





$$\Gamma_{\mathrm{NLO}}(h \to Z\ell\ell) = \sin^2(\beta - \alpha) \times \Gamma_{\mathrm{NLO}}(h \to Z\ell\ell)_{\mathrm{SM}}$$

Renormalization conditions $\Delta_{\mathrm{EW}}^{\tau} = \Delta_{\mathrm{EW}}^{\tau}|_{\mathrm{SM}} \quad \Delta_{\mathrm{EW}}^{Z\ell\ell} = \Delta_{\mathrm{EW}}^{Z\ell\ell}|_{\mathrm{SM}}$

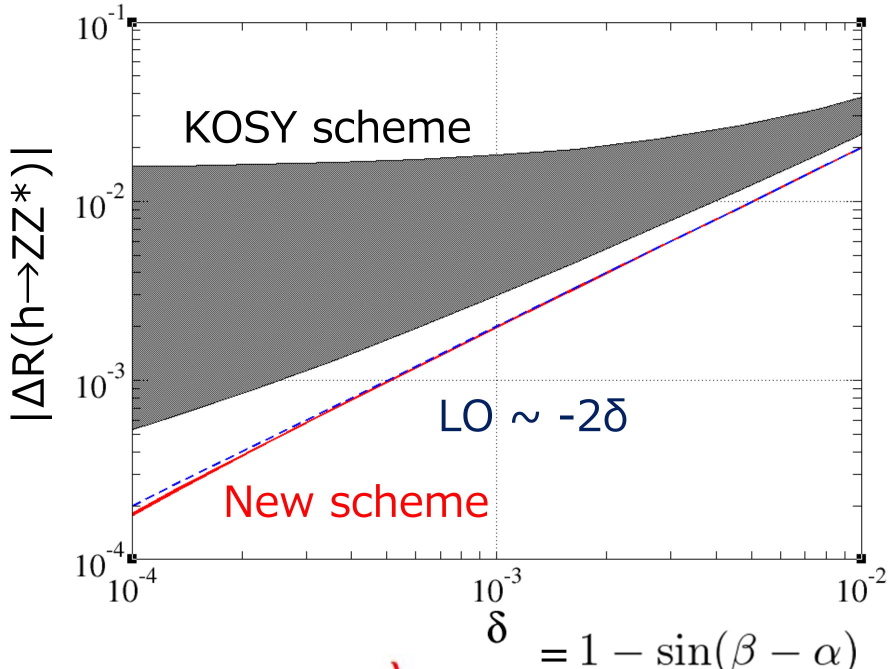
Deviation in the h → VV* decays

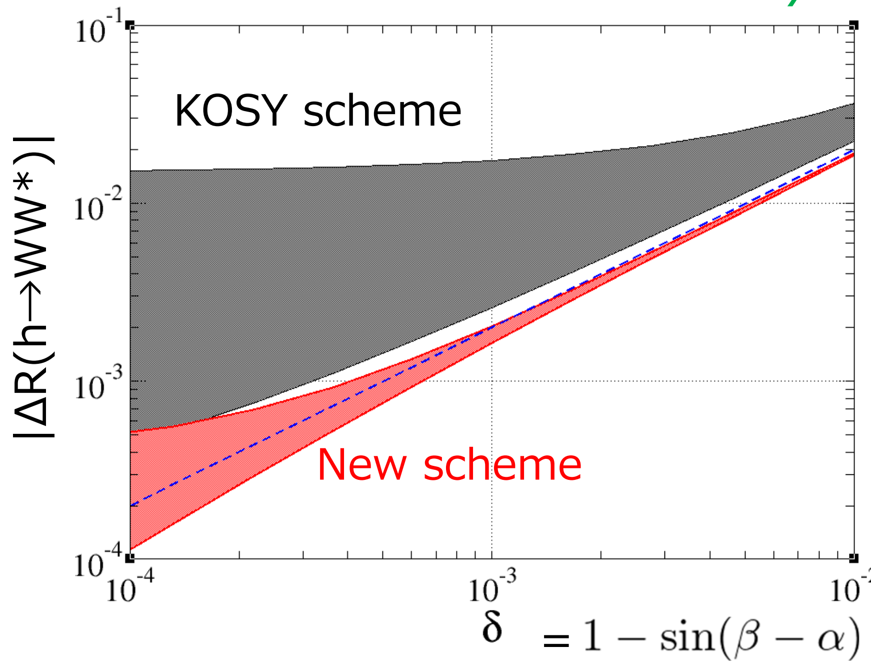
Using H-COUP v3 with modifications

Type-I 2HDM, $m_{H+} = m_H = m_A = 300$ GeV, $\tan\beta = 2$, $0 < M^2 < (300\ \text{GeV})^2$

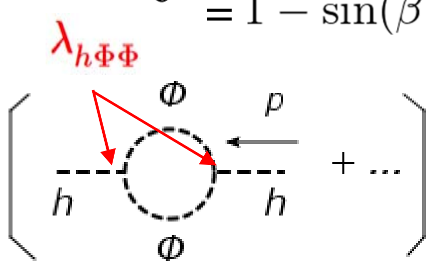
$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)}{\Gamma_{\rm SM}(h \to XX)} - 1$$

Preliminary





$\delta Z_h = -\frac{d}{dp^2}$



$p^2 = m_h^2$

$$\propto -\frac{1}{16\pi^2}\frac{\lambda^2_{h\Phi\Phi}}{m^2_\Phi} \sim -\frac{1}{16\pi^2}\frac{m^2_\Phi}{v^2}\left(1 - \frac{M^2}{m^2_\Phi}\right)^2$$

Deviation in the h → ff decays (Type-I)

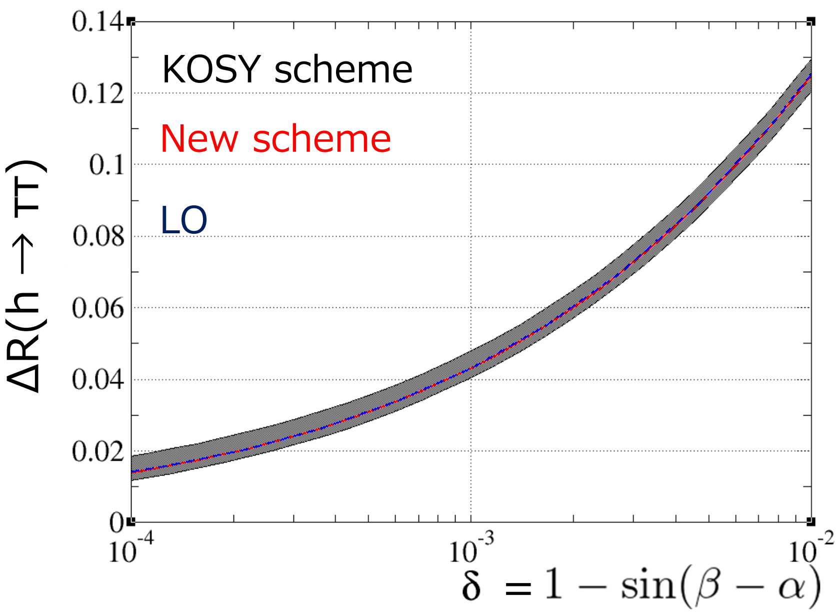
Using H-COUP v3 with modifications

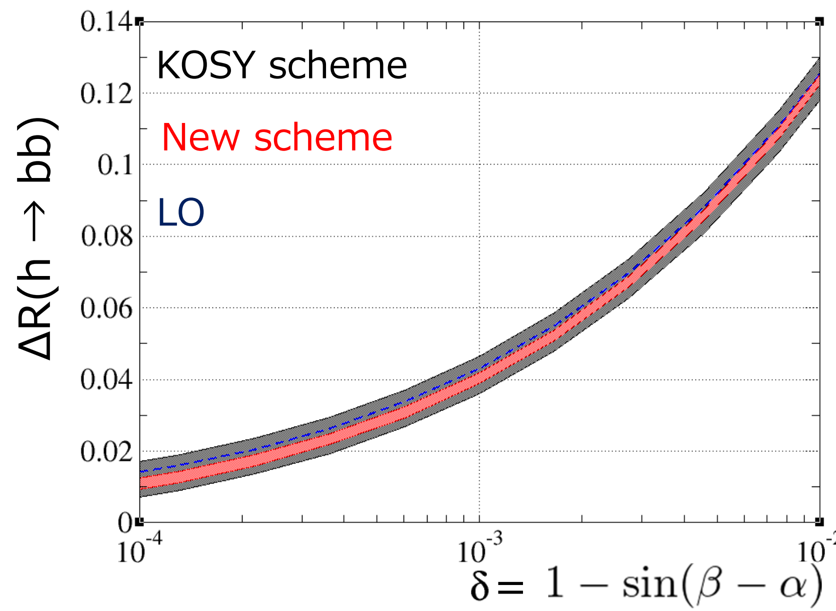
Type-I 2HDM, $m_{H+} = m_H = m_A = 300$ GeV,
tanβ = 2, $0 < M^2 < (300\text{ GeV})^2$

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)}{\Gamma_{\rm SM}(h \to XX)} - 1$$

$$\kappa_f^h - 1 \sim \sqrt{2\delta} \cot\beta + \mathcal{O}(\delta)$$

Preliminary





h → cc is almost the same as h → τ τ

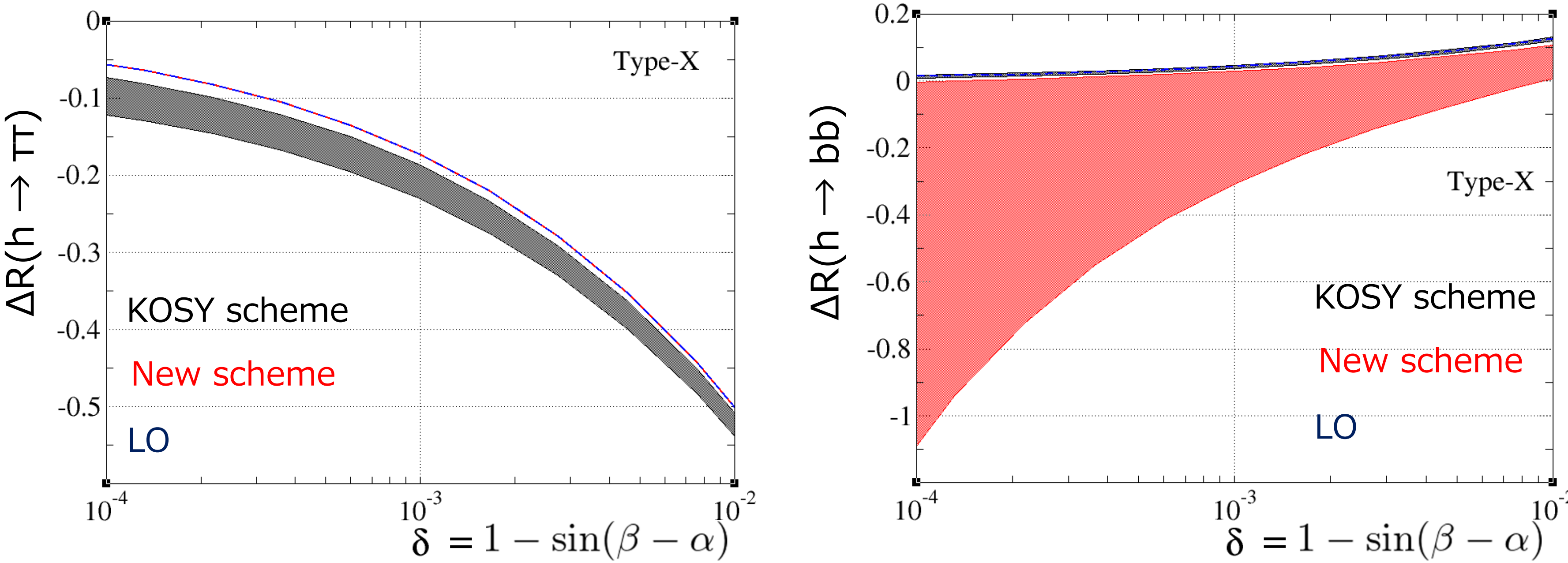
Deviation in the h → ff decays (Type-X)

Using H-COUP v3 with modifications

Type-X 2HDM, $m_{H+} = m_H = m_A = 300$ GeV,
$\tan\beta = 2$, $0 < M^2 < (300\ \text{GeV})^2$

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)}{\Gamma_{\text{SM}}(h \to XX)} - 1$$

Preliminary



$$\Delta^b_{\text{EW}} \supset \frac{\delta Z_h}{\cos(\beta-\alpha)} \cot\beta \simeq -\frac{1}{16\pi^2}\frac{m_\Phi^2}{v^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^2 \frac{\cot\beta}{\sqrt{\delta}}$$

Summary

- Generally, mixing angles loose the meaning of alignmentness at quantum levels.

- We proposed the new renormalization scheme in the 2HDM, where $\delta\alpha$ and $\delta\beta$ are determined by using the $h \to \tau\tau$ and $h \to Zll$ decay rates at NLO.

$$\Gamma_{\rm NLO}(h \to \tau\tau) = (\kappa_h^\tau)^2 \times \Gamma_{\rm NLO}(h \to \tau\tau)_{\rm SM}$$

$$\Gamma_{\rm NLO}(h \to Z\ell\ell) = \sin^2(\beta-\alpha) \times \Gamma_{\rm NLO}(h \to Z\ell\ell)_{\rm SM}$$

- The deviations in the $h \to VV^*$ and $h \to \tau\tau$ decays are well described by $\sin(\beta-\alpha)$ and κ_h^τ even at NLO, while the deviation in $h \to qq$ depends on the type of Yukawas and type of fermions.

Backup slides

Previous scheme (KOSY scheme)

Kanemura, Okada, Senaha, Yuan (2004)

Field shifts are performed as follows (e.g. CP-even part):

$$\begin{pmatrix} H_B \\ h_B \end{pmatrix} = R(-\alpha_B)\begin{pmatrix} h_{1B} \\ h_{2B} \end{pmatrix} = R(-\delta\alpha)R(-\alpha_R)\tilde{Z}\begin{pmatrix} h_{1R} \\ h_{2R} \end{pmatrix} = R(-\delta\alpha)\underbrace{R(-\alpha_R)\tilde{Z}R(\alpha_R)}_{=Z}\begin{pmatrix} H_R \\ h_R \end{pmatrix}$$

$$Z = \begin{pmatrix} 1+\frac{\delta Z_H}{2} & \delta C_{Hh} \\ \delta C_{hH} & 1+\frac{\delta Z_h}{2} \end{pmatrix} \Rightarrow R(-\delta\alpha)Z = \begin{pmatrix} 1+\frac{\delta Z_H}{2} & \delta C_{Hh}+\delta\alpha \\ \delta C_{hH}-\delta\alpha & 1+\frac{\delta Z_h}{2} \end{pmatrix}$$

@ 1-loop level

We then identify the W.F. renormalization factors as

CP-even:

$$\delta Z_{Hh} = \delta C_{Hh} + \delta\alpha$$
$$\delta Z_{hH} = \delta C_{hH} - \delta\alpha$$

CP-odd:

$$\delta Z_{GA} = \delta C_{GA} + \delta\beta$$
$$\delta Z_{AG} = \delta C_{AG} - \delta\beta$$

Charged:

$$\delta Z_{G^\pm H^\mp} = \delta C_{G^\pm H^\mp} + \delta\beta$$
$$\delta Z_{H^\pm G^\mp} = \delta C_{H^\pm G^\mp} - \delta\beta$$

Assumptions: $\delta C_{Hh} = \delta C_{hH}$, $\delta C_{GA} = \delta C_{AG}$, $\delta C_{G^\pm H^\mp} = \delta C_{H^\mp G^\pm}$

In total, we have 21 conditions.

→ Relaxing one of the OS cond. III, all the CTs are determined.

In the new scheme, we take δC_{ij} & δC_{ji} or δZ_{ij} & δZ_{ji} ($i \neq j$) independently.

Prediction?

- The mixing counterterms are determined by

$$\delta_{\rm SM}^{Z} = \frac{\delta Z_h}{2} - \frac{\delta v}{v} + \frac{\delta m_Z^2}{m_Z^2} + \delta Z_Z$$

$$\delta_{\rm SM}^{\tau} = \frac{\delta Z_h}{2} - \frac{\delta v}{v} + \frac{\delta m_\tau}{m_\tau} + \delta Z_V^{\tau}$$

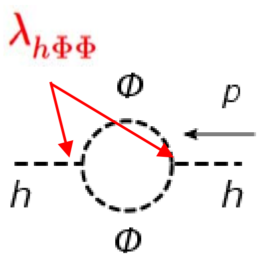
$$\delta(\beta-\alpha) = -\delta Z_{Hh} - t_{\beta-\alpha}\left[\delta_{\rm SM}^{Z} + \frac{\Gamma_{hZZ}^{1,1{\rm PI}}\big|_{\rm div}}{\Gamma_{hZZ}^{1,{\rm tree}}} + \frac{\Delta_{\rm rem}^{Z\ell\ell} - \Delta_{\rm EW}^{Z\ell\ell}\big|_{\rm SM}}{2}\right]$$

$$\delta\beta = \frac{\kappa_\tau^h}{(1+\zeta_\tau^2)c_{\beta-\alpha}}\left[\delta_{\rm SM}^{\tau} + \frac{\Gamma_{h\tau\tau}^{S,1{\rm PI}}\big|_{\rm div}}{\Gamma_{h\tau\tau}^{S,{\rm tree}}} + \frac{\Delta_{\rm rem}^{\tau} - \Delta_{\rm EW}^{\tau}\big|_{\rm SM}}{2} + \frac{\kappa_\tau^H}{\kappa_\tau^h}[\delta(\beta-\alpha) + \delta Z_{Hh}]\right]$$

- The other h decays (h → WW*, bb, cc, etc.) are the predictions.

$$\Delta_{\rm EW}^{Wff} = 2\left(\frac{\delta m_W^2}{m_W^2} - \frac{\delta m_Z^2}{m_Z^2} + \delta Z_W - \delta Z_Z\right)_{\rm fin} + \Delta_{\rm rem}^{Wff} - \Delta_{\rm rem}^{Z\ell\ell} + \Delta_{\rm EW}^{Z\ell\ell}\big|_{\rm SM}$$

The dominant contribution **δZ_h** vanishes in the new scheme.

$\delta Z_h = -\frac{d}{dp^2}\left[\right.$ 

$\left. + \ldots\right]_{p^2 = mh^2}$ $\propto -\frac{1}{16\pi^2}\frac{\lambda_{h\Phi\Phi}^2}{m_\Phi^2} \sim -\frac{1}{16\pi^2}\frac{m_\Phi^2}{v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^2$

⇒ O(1)% for $M/m_\Phi \ll 1$

EW corrections to h → ff

For $\zeta_f = \zeta_\tau$

$$\Delta_{\rm EW}^f = 2\left(\frac{\delta m_f}{m_f} - \frac{\delta m_\tau}{m_\tau} + \delta Z_V^f - \delta Z_V^\tau\right)_{\rm fin} + \Delta_{\rm rem}^f - \Delta_{\rm rem}^\tau + \Delta_{\rm EW}^\tau|_{\rm SM}$$

Again, the δZ_h term vanishes.

$x = \pi/2 - (\beta - \alpha)$

$\cos(\beta - \alpha) \sim x$

For $\zeta_f = -\frac{1}{\zeta_\tau}$

$$\begin{aligned}\Delta_{\rm EW}^f = 2\Bigg[&\frac{\delta m_f}{m_f} - \zeta_f^2\frac{\delta m_\tau}{m_\tau} + \delta Z_V^f - \zeta_f^2\delta Z_V^\tau + \underline{2\zeta_f\left(\frac{1}{x} - \zeta_f\right)\left(\frac{\delta Z_h}{2} - \frac{\delta v}{v}\right)} \\ &+ \left(\frac{2\zeta_f}{x} - 1 - \zeta_f^2\right)\left(\frac{\delta m_Z^2}{m_Z^2} + \delta Z_Z\right)\Bigg]_{\rm fin} \\ &+ \Delta_{\rm rem}^f - \zeta_f^2(\Delta_{\rm rem}^\tau - \Delta_{\rm EW}^\tau|_{\rm SM}) + \left(\frac{2\zeta_f}{x} - 1 - \zeta_f^2\right)(\Delta_{\rm rem}^{Z\ell\ell} - \Delta_{\rm EW}^{Z\ell\ell}|_{\rm SM}) + \mathcal{O}(x)\end{aligned}$$

The δZ_h term appears and it is enhanced by the factor of 1/x.

Non-decoupling effects on hhh

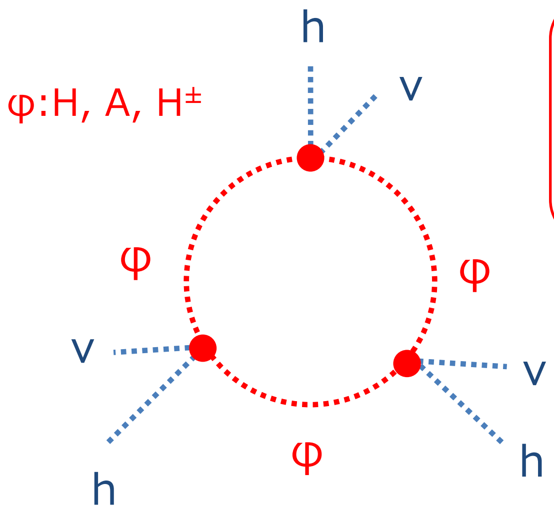
Kanemura, Okada, Senaha, Yuan (2004)

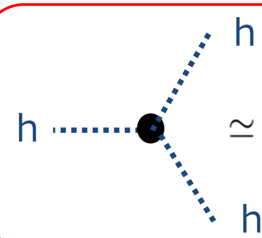
2-loop calculations:

Braathen, Kanemura (2019)

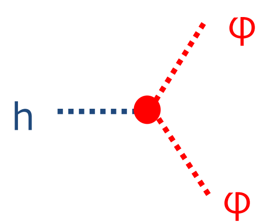
Bahl, Braathen, Weiglein (2022)

- 1-loop correction to hhh





$$\simeq \lambda_{hhh}^{\rm SM} \times \left(1 - \frac{4M^2 - m_h^2}{2m_h^2} c_{\beta-\alpha}^2\right)$$



$$\simeq \frac{M^2 - m_\varphi^2}{v}$$

$$\simeq \frac{1}{32\pi^2} \sum_\varphi c_\varphi \frac{\lambda_{h\varphi\varphi}^3}{m_\varphi^2} \qquad c_\varphi = 2(1) \text{ for } H^\pm \ (H, A)$$

$$= -\frac{1}{32\pi^2} \sum_\varphi c_\varphi \frac{m_\varphi^4}{v^3} \left(1 - \frac{M^2}{m_\varphi^2}\right)^3$$

$\sim \dfrac{\boldsymbol{v^3}}{\boldsymbol{M^2}}$ Decoupling case (M ~ m_φ)

$\sim \dfrac{\boldsymbol{m_\varphi^4}}{\boldsymbol{v^3}}$ Non-dec. case (M « m_φ)

This m_φ^4-like effect appears in both the KOSY & the new schemes.

Renormalized hhh coupling

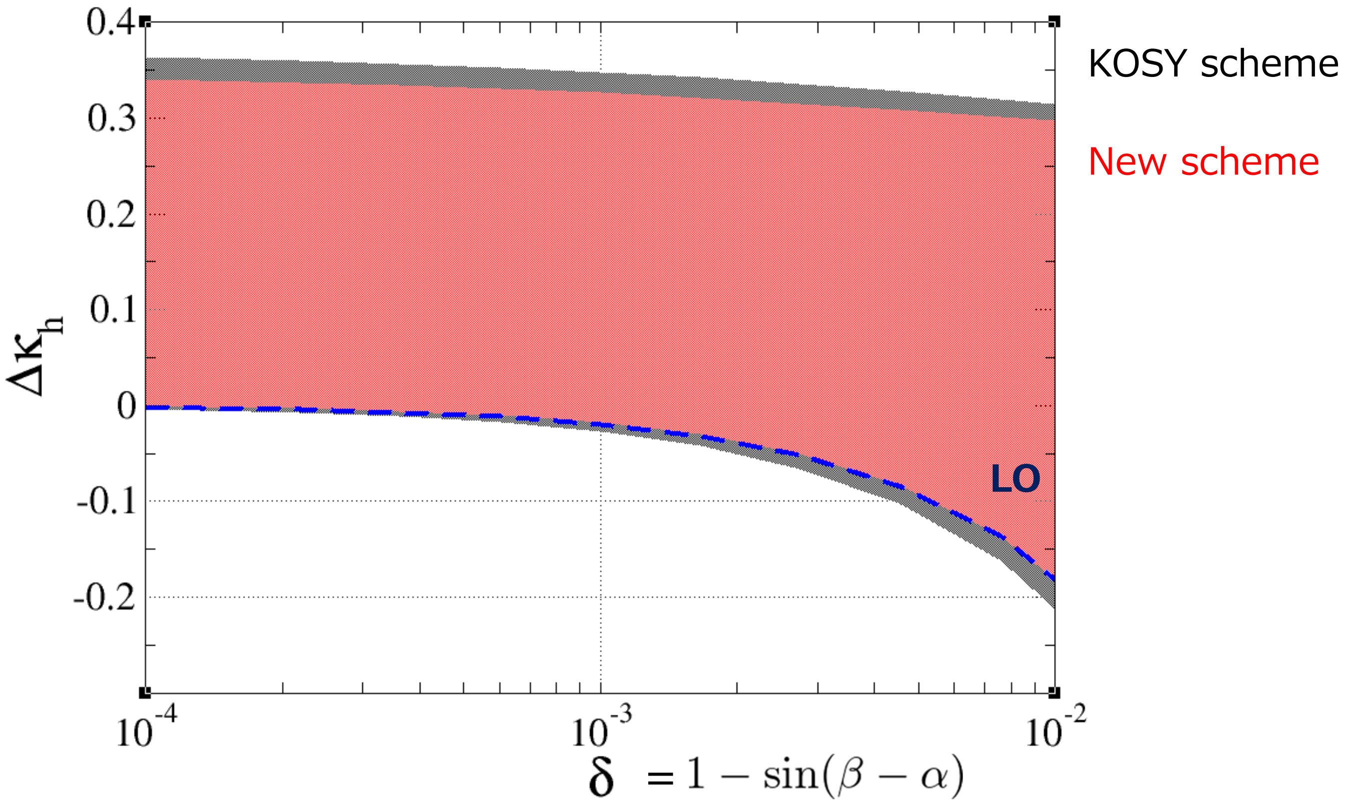
Using H-COUP v3 with modifications

Type-I 2HDM, $m_{H+} = m_H = m_A = 300$ GeV,

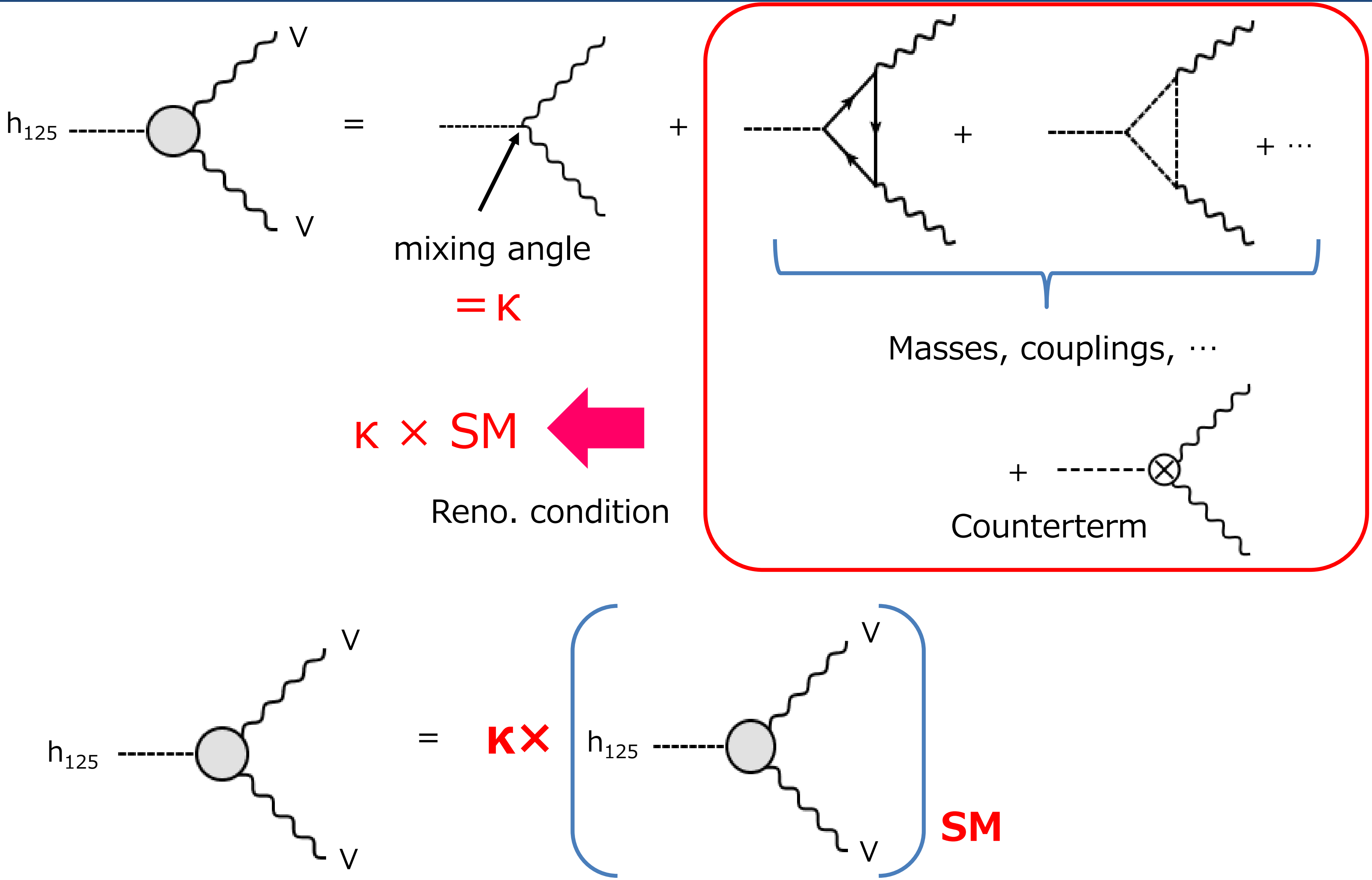
$\tan\beta = 2$, $0 < M^2 < (300\ \text{GeV})^2$

$$\Delta\kappa_h = \frac{\hat{\Gamma}_{hhh}}{\hat{\Gamma}^{\text{SM}}_{hhh}} - 1$$

Preliminary



Key idea



h_{125}
V
V
=
mixing angle
$=\kappa$
+
+
+ ⋯
Masses, couplings, ⋯
+
Counterterm
$\kappa \times$ SM
Reno. condition
h_{125}
V
V
=
$\kappa\times$
h_{125}
V
V
SM